U S D A FOREST SERVICE
RESEARCH NOTE RM- 207

FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE

ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION

Derivation of the 1- and 10-Hour Timelag Fuel Moisture Calculations for Fire-Danger Rating

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Procedures for calculating the moisture contents of 1- and 10-hour timelag fuels have been developed based on theoretical calculations of the rate of moisture transport in wood. The 1-hour timelag calculation is superior to fine fuel moisture calculations developed previously because there is no regional bias, making it valid over a wider range of conditions, and because it separates out the effects of the environmental factors of temperature, humidity, and solar radiation. The 10-hour timelag calculation produced values reasonably consistent with observations obtained from 1/2-inch ponderosa pine fuel sticks exposed under field conditions.

KEY WORDS: Forest fuels, forest fire hazard, fuelwood.

Fuel moisture content is one of the major variables in evaluating fire danger and predicting fire behavior. Rothermel's[2] development of a mathematical model for predicting fire spread in a heterogeneous fuel and its subsequent adaptation to fire-danger rating require moisture inputs for more than one class of fuel. Dead fuels have been classified by their moisture timelag for fire-danger rating.[3] These fuel classes are the 1-, 10-, and 100-hour classes, which correspond roughly to cylindrical fuels less than 1/4 inch in diameter, 1/4 to 1 inch, and 1 to 3 inches in diameter, respectively.

In the past, these fuels have been represented by physical analogs; basswood slats for fine or 1-hour timelag fuels, half-inch ponderosa pine fuel sticks for the intermediate or 10-hour timelag fuels, and 2-inch ponderosa pine dowels for the heavier 100-hour timelag fuels (Gis-

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[2] *Rothermel, R. C. A mathematical model for fire spread predictions in wildland fuels. 1971. (Unpublished report on file at N. Forest Fire Lab., U. S. Dep. Agr., Forest Serv., Missoula, Mont.)*

[3] *Fosberg, Michael A., James W. Lancaster and Mark J. Schroeder. Dead forest fuels characterization by moisture timelag. (Manuscript in preparation.)*

borne 1936). A computational system is needed, however, because field use of physical analogs is not always feasible, and direct measurements are seldom available when analyzing records for fire-danger ratings. Past work has produced two schemes for estimating the moisture contents of fuels in the 1-hour group. One consists of regression equations based on field measurements of basswood slats (Storey 1965),[4/] the other consists of a weighted average of the equilibrium moisture value for wood corresponding to the ambient dry bulb temperature and humidity, and the observed moisture content of a half-inch ponderosa pine fuel stick.[5/] In general, computational schemes have not been used operationally to represent the 10-hour timelag fuel moisture, although one has been developed (Storey 1965). The 100-hour timelag fuel has generally been represented by a buildup index in some form. Fosberg (1971) developed a direct computational scheme for this fuel.

Previously developed computational systems were generally not well suited for universal application because the derived relationships were based on limited ranges of environmental conditions characteristic of specific geographic areas. Thus, for nationwide application, the resultant regression equations had to be extrapolated beyond the ranges of data. This limitation is overcome by use of the general solution developed by Fosberg et al. (1970) and Fosberg (1971).

The General Theory

The basic theoretical solution for moisture gain and loss is

$$\frac{\delta m}{\Delta m} = 1-\zeta e^{-\lambda t} \qquad (1)$$

where the relationship between change in moisture content, $\delta m = m_{i+1} - m_i$, and the difference between the surface moisture content and the initial moisture content, $\Delta m = mb_{i+1} - m_i$, is a simple exponential function. In this expression, m_{i+1} is the moisture content at the end of the change period, $i+1$, m_i is the moisture content at the beginning, and mb_{i+1} is the moisture content of the surface fibers at the end. ζ is the similarity coefficient, λ is the inverse of the timelag, and t is the time period over which the moisture exchange takes place. The similarity coefficient is dependent on the product λt. ζ is derived empirically and is used to insure the value of $\delta m/\Delta m$ which is considered a nondimensional constant. Stable solutions exist only over the interval $.05 < \lambda t \leq 0\ 0.5$. This implies that, for 1-hour timelag fuels, the moisture contents may be predicted for periods of one-half hour or less. Since we are interested in predictions for much longer periods, these short-period predictions must be assembled sequentially. To do this we solve equation (1) for the moisture content at the end of a time step $i+1$. δt is the length of the time step; $t = i\,\delta t$.

$$\delta m = \Delta m(1-\zeta e^{-\lambda\delta t})$$

$$m_{i+1} - m_i = (1-\zeta e^{-\lambda\delta t})(mb_{i+1} - m_i)$$

$$m = (1-\zeta e^{-\lambda\delta t})(mb_{i+1} - m_i) + m_i$$

For notational convenience, let $\chi = 1-\zeta e^{-\lambda\delta t}$, thus

$$m_{i+1} = \chi(mb_{i+1} - m_i) + m_i$$

$$m_{i+1} = \chi mb_{i+1} + m_i\ (1-\chi) \qquad (2)$$

To solve for the moisture content after a number of time steps, $i+0,\ 1,\ 2, --,\ n-1,\ n$;

$$m_1 = \chi mb_i + m_0(1-\chi)$$

and

$$m_2 = \chi mb_2 + m_1(1-\chi)$$

$$\vdots$$

$$m_{n-1} = \chi mb_{n-1} + m_{n-2}(1-\chi)$$

$$m_n = \chi mb_n + m_{n-1}(1-\chi)$$

where the initial value for each subsequent step is the final moisture content from the previous computation. These individual solutions may be combined to give a solution of the general form:

$$m_n = \chi[mb_n + \sum_{j=1}^{n-1}(1-\chi)^j mb_{n-j}] + (1-\chi)^n m_o \qquad (3)$$

4/ U. S. Forest Service. Washington Office, Division of Fire Control. Derivation of spread phase tables. National Fire-Danger Rating System. 54 p. 1966. (Unpublished report on file at Rocky Mt. Forest and Range Exp. Sta., U. S. Dep. Agr., Forest Serv., Fort Collins, Colo.)

5/ U. S. Forest Service. Wildland fire danger rating. n.d., n.p. Pac. Southwest Forest and Range Exp. Sta., Berkeley, Calif.

Where j is the interval of summation; $j=n-i$.

Equation (3) may be simplified by first considering that no precipitation occurs. This assumption may at first seem unduly restrictive, but the effect of precipitation can be added later.

Since drying conditions preceding the time for which the fuel moisture is to be evaluated are cyclic, a consideration of that variation must be incorporated in the computation. This is accomplished by defining and computing a climatological coefficient c_{n-j} which is the ratio of the equilibrium moisture content at the end of time step i, me_{n-j} and the equilibrium moisture content at the end of time step n, me_n

$$c_{n-j} = \frac{me_{n-j}}{me_n}$$

The moisture content at the immediate surface of the fuel element is governed by the environment and, for all practical purposes, is the equilibrium moisture content. Except when it is raining, m_b then can be set equal to m_e . Thus , equation (3) becomes

$$m_n=\chi[me_n+\sum_{j=1}^{n-1}(1-\chi)^j me_{n-j}]+(1-\chi)^n m_o$$

with

$$me_{n-j} = me_n \; c_{n-j}$$

$$m_n=\chi[me_n+me_n \sum_{j=1}^{n-1}(1-\chi)^j c_{n-j}]+(1-\chi)^n m_o$$

$$m_n=\chi me_n[1+\sum_{j=1}^{j=n-1}(1-\chi)^j c_{n-j}]+(1-\chi)^n m_o \quad (4)$$

and the term $(1-\chi)^n \; m_o$ becomes very small and can be neglected. The precipitation effects are now added by going back to equation (1) and determining a moisture change, dmp , due to precipitation.

$$dmp_{i+1} = \chi mb_{i+1} + m_i(1-\chi)$$

6/ *A laboratory experiment showed a linear relationship between the wetting boundary conditions mb and the duration of wetting td. The constants a and b were empirically derived from these wetting experiments for both 1/2-inch and 2-inch ponderosa pine dowels.*

7/ *The Kronecker delta is a mathematical notation used to denote a situation where there are two or more possible conditions which are mutually exclusive, i.e., valid or nonvalid, existent or nonexistent. In this case it denotes rain or no rain.*

This again must be solved in series. Thus wetting becomes

$$dmp_n = \chi \sum_{j=1}^{n-1} \delta_i (1-\chi)^j \; mb_{n-j} \quad (5)$$

where mb is the wetting boundary condition,6/ $mb = a+b \; t_{di}$ where t_{di} is the duration of the precipitation during time step i . The Kronecker delta,7/ δ_i , is "0" if there is no precipitation during the time step i and is "1" if there is precipitation. The dmp_n given by equation (5) is added to the m_n from equation (4) to give the total moisture content.

Application of the General Theory to Field Problems

The solutions provided by equations (4) and (5) may be obtained for the particular cases of the 1- and 10-hour timelag fuels. The solution is obtained by specifying the similarity coefficient, ζ , from laboratory studies, and the timelag, λ^{-1}, the time increment, δt , and the climatological coefficient, c_{n-j} for a 1430 LST observation. For the 1-hour timelag fuel, 12 time steps of ½-hour duration were used. Thus, $\zeta=1, \lambda=1, \delta t=0.5$, and the term $\chi=0.3935$. The climatological coefficients are averages computed from data taken during six general observation periods of the O'Neill, Nebraska, Great Plains Study (Lettau and Davidson 1957). The standard weather shelter temperature and humidity readings were converted to equilibrium moisture content (U. S. Forest Service 1955). These coefficients (fig. 1) could then be substituted into equation (4) to give the resultant equation

$$m = 1.0329 \; me \quad (6)$$

for a midafternoon observation.

Since the equilibrium moisture content depends only on temperature and humidity, a table readily usable in the field may be constructed (table 1). Since the temperature and humidity are measured in shelters 4½ feet above the ground, and the moisture content of the fuel depends on the temperature and humidity of the air immediately in contact with its surface, the shelter readings must be corrected to account for the temperature and moisture lapse rates between the levels of the instruments and the surface of the fuels on sunny

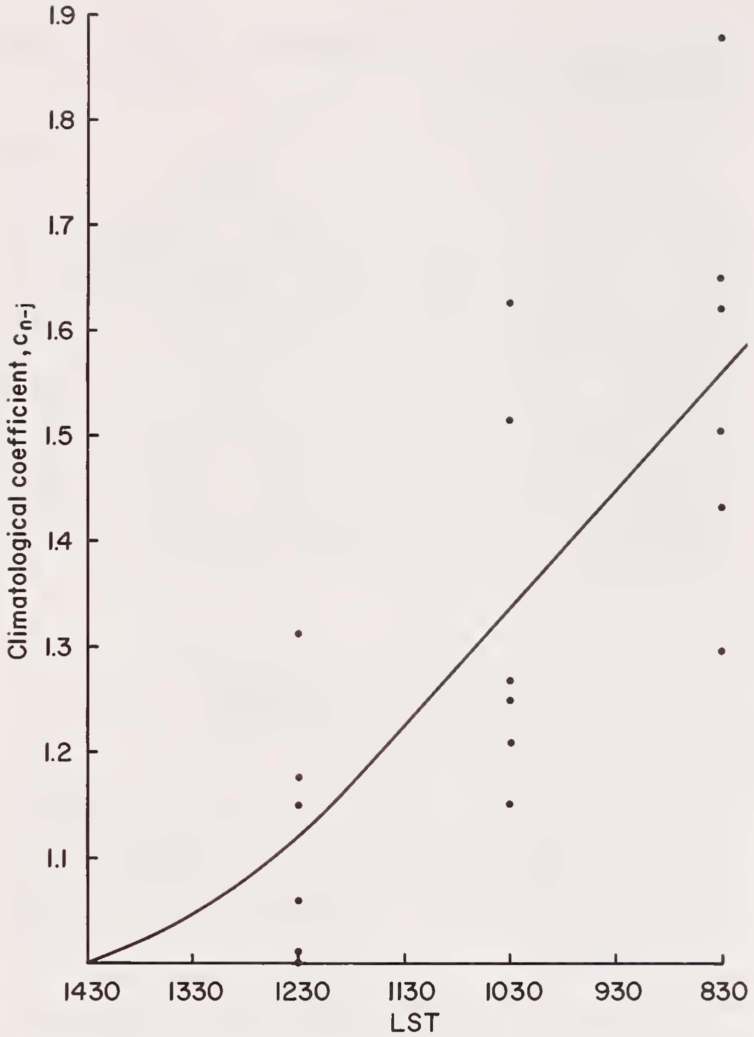


Figure 1.--The climatological coefficients, c_{n-j}, for a 1430 LST observation. The data points are the coefficients calculated from the bi-hourly observations for six observation periods of the O'Neill, Nebraska, Great Plains study (Lettau and Davidson 1957).

days. The temperature and moisture lapse rates depend on a number of variables not considered because of the complexity that would result. They are windspeed, aspect, slope, stability, and the radiation absorption and emission characteristics of the underlying surface. The averages of values found in the literature result in corrections of 15° F. increase in temperature and a 3° F. increase in dew point temperature (Geiger 1957). These yield an adjusted relative humidity which is 75 percent of the shelter value.

Increases in moisture content due to precipitation are difficult to compute for the 1-hour timelag fuel because, first, precipitation duration must be known to the nearest half-hour, and, second, the duration must be applied to the particular time steps in which it occurred. The second difficulty is the most restrictive because it would require solution of the series or a very large number of tables to provide for all contingencies. Neither of these are practical. A straightforward alternative is to assume that, when it is raining, the fuels are at fiber saturation or 30 percent moisture content.

Calculation of the 10-hour timelag fuel moisture followed the same procedures except that six 4-hour time steps were used. Thus $\delta t=4$, $\lambda=0.1$, and $\zeta=.98$, giving a value of $\chi=.3431$. The climatological coefficients were determined from the same source and in the same manner as for the 1-hour timelag fuels. This gives a

Table 1.--One-hour timelag fuel moisture (percent)

State of weather[1/]			Relative humidity (percent)																				
	Code 0-1 Temperature	Code 2-9 Temperature	0→4	5→9	10→14	15→19	20→24	25→29	30→34	35→39	40→44	45→49	50→54	55→59	60→64	65→69	70→74	75→79	80→84	85→89	90→94	95→99	100
SUNNY	10→29		1	2	2	3	4	5	5	6	7	8	8	8	9	9	10	11	12	12	13	13	14
SUNNY	30→49		1	2	2	3	4	5	5	6	7	7	7	8	9	9	10	10	11	12	13	13	13
SUNNY	50→69		1	2	2	3	4	5	5	6	6	7	7	8	8	9	9	10	11	12	12	12	13
SUNNY	70→89		1	1	2	2	3	4	5	5	6	7	7	8	8	8	9	10	10	11	12	12	13
SUNNY	90→109		1	1	2	2	3	4	4	5	6	7	7	8	8	8	9	10	10	11	12	12	13
SUNNY	109+		1	1	2	2	3	4	4	5	6	7	7	8	8	8	9	10	10	11	12	12	13
CLOUDY		10→29	1	2	4	5	5	6	7	8	9	10	11	12	12	14	15	17	19	22	25	25+	25+
CLOUDY		30→49	1	2	3	4	5	6	7	8	9	9	11	11	12	13	14	16	18	21	24	25+	25+
CLOUDY		50→69	1	2	3	4	5	6	6	8	8	9	10	11	11	12	14	16	17	20	23	25+	25+
CLOUDY		70→89	1	2	3	4	4	5	6	7	8	9	10	10	11	12	13	15	17	20	23	25+	25+
CLOUDY		90→109	1	2	3	3	4	5	6	7	8	9	9	10	10	11	13	14	16	19	22	25	25+
CLOUDY		109+	1	2	2	3	4	5	6	6	8	8	9	9	10	11	12	14	16	19	21	24	25+

1/ In recording fire-weather observational data, the "state of weather" code 0 indicates a clear sky and 1 indicates 5/10s or less cloud cover; both are in the general condition "Sunny." 2 through 9 indicate more than 5/10s cloud cover and various conditions of precipitation, generally included here under "cloudy."

prediction equation for the moisture content of the 10-hour timelag fuels of

$$m = 1.2815\ me \qquad (7)$$

for a midafternoon observation. As with the 1-hour timelag fuel, shelter readings were corrected to account for temperature and humidity profiles on sunny days.

The effect of precipitation on the 10-hour timelag fuel was determined by considering precipitation durations of 1 to 4 hours in each of the six periods beginning at the time of the observation used to rate the day, usually in the early afternoon. These increases in moisture content were sufficiently stable to allow the 24-hour period from one observation to the next to be split into a first 16-hour period and a final 8-hour period, which is much more practical for field use where accurate rainfall occurrence records are not easily attainable. The table for field use (table 2) is similar in format to that used to calculate the 1-hour timelag fuel moisture. If precipitation occurs, part B of the table is used, and the correction for precipitation is added to the results derived from part A.

Certain errors result when the computations are made with data from the tables generated for field use. The final term in equation (4) is not always negligible for the 10-hour timelag fuel. The error made in neglecting this term becomes noticeable only when the moisture content is well above fiber saturation, a situation that is not important in fire-danger rating, however, since fuels with moisture contents above this value can be considered, for all practical purposes, to be fireproof. Breaking the day

Table 2.--Ten-hour timelag fuel moisture (percent)

Part A[1/]

State of weather: Code 0-1 Temperature	State of weather: Code 2-9 Temperature	0→4	5→9	10→14	15→19	20→24	25→29	30→34	35→39	40→44	45→49	50→54	55→59	60→64	65→69	70→74	75→79	80→84	85→89	90→94	95→99	100
SUNNY 10→29		1	2	4	5	6	6	7	8	9	9	10	11	12	13	14	14	15	16	17	18	20
SUNNY 30→49		1	2	3	5	6	6	7	8	9	9	10	11	12	12	13	14	15	16	17	18	20
SUNNY 50→69		1	2	3	4	5	6	7	8	8	9	10	11	11	12	13	13	14	15	16	17	19
SUNNY 70→89		1	1	3	4	5	5	6	7	8	8	9	10	11	12	12	13	14	14	16	16	18
SUNNY 90→109		1	1	3	4	4	5	6	7	8	8	9	10	11	11	12	12	13	13	15	16	18
SUNNY 109+		1	1	3	3	4	5	6	7	7	8	9	10	10	11	11	12	13	13	15	15	17
	CLOUDY 10→29	1	2	5	6	7	8	9	10	11	12	13	14	15	17	18	20	23	25+	25+	25+	25+
	CLOUDY 30→49	1	2	5	6	7	8	9	10	11	12	13	14	15	16	18	20	23	25	25+	25+	25+
	CLOUDY 50→69	1	2	4	5	6	7	8	9	10	11	13	13	14	16	17	19	22	24	25+	25+	25+
	CLOUDY 70→89	1	2	4	5	6	7	8	9	10	11	12	13	14	15	16	18	21	24	25+	25+	25+
	CLOUDY 90→109	1	2	3	4	5	7	8	9	10	11	11	12	13	14	16	18	20	23	25+	25+	25+
	CLOUDY 109+	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	17	20	22	25	25+	25+

Part B[2/]

Time precipitation occurred	Precipitation duration (hours): 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Basic observation yesterday to 0600 today	2	4	7	9	11	14	16	18	20	23	25	25+	25+	25+	25+	25+
0600 today to basic observation today	7	15	22	25+	25+	25+	25+	25+	--	--	--	--	--	--	--	--

1/ If no precipitation has occurred since basic observation time yesterday, today's 10-hour timelag fuel moisture is read directly from this part of the table.

2/ When precipitation occurs, add the results from this part of the table to the results of part A. The sum is today's 10-hour timelag fuel moisture value.

into 16-hour and 8-hour periods instead of six 4-hour periods for computing the contributions of rain to the 10-hour timelag fuel moisture accounts for much of the error in this computation. The reason is that the magnitude of the precipitation contribution to the final answer is highly dependent on when the precipitation occurs. The error is such that short-period rainfall effects are overestimated if they occur 16 hours or longer before the observation, and are underestimated if they occur within 4 hours of observation time.

Evaluation and Comparison of the Predictions

The 1-hour timelag fuel moisture predictions have not been compared to field data. Instead, they are compared to the fine fuel moisture calculations used in the wildland fire-danger system used in California and to the fine fuel moisture calculations developed by Storey (1965) and used in the 1964 version of the National Fire-Danger Rating System. These comparisons (fig. 2) show that predictions developed here compare well with both in general, but that under condi-

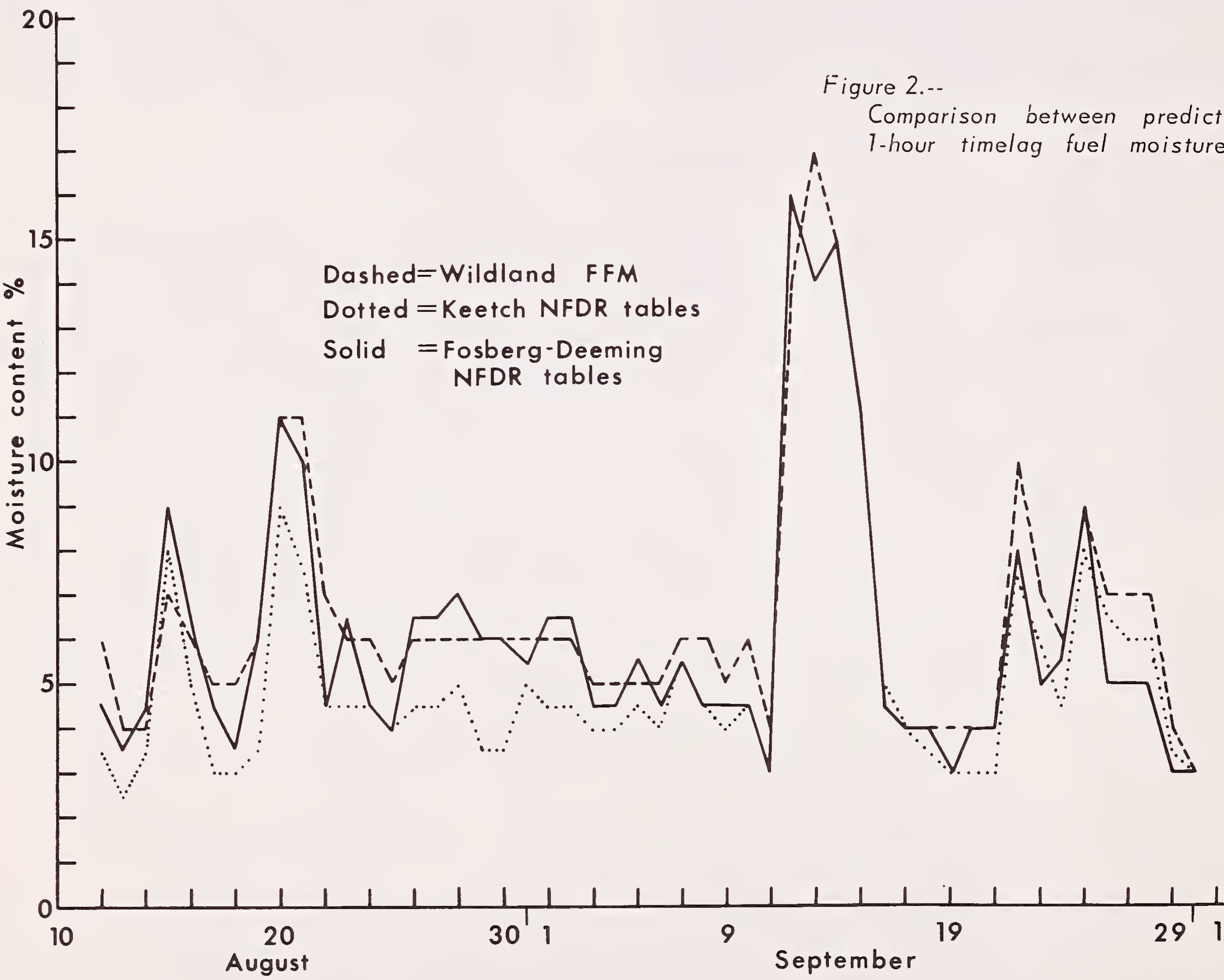


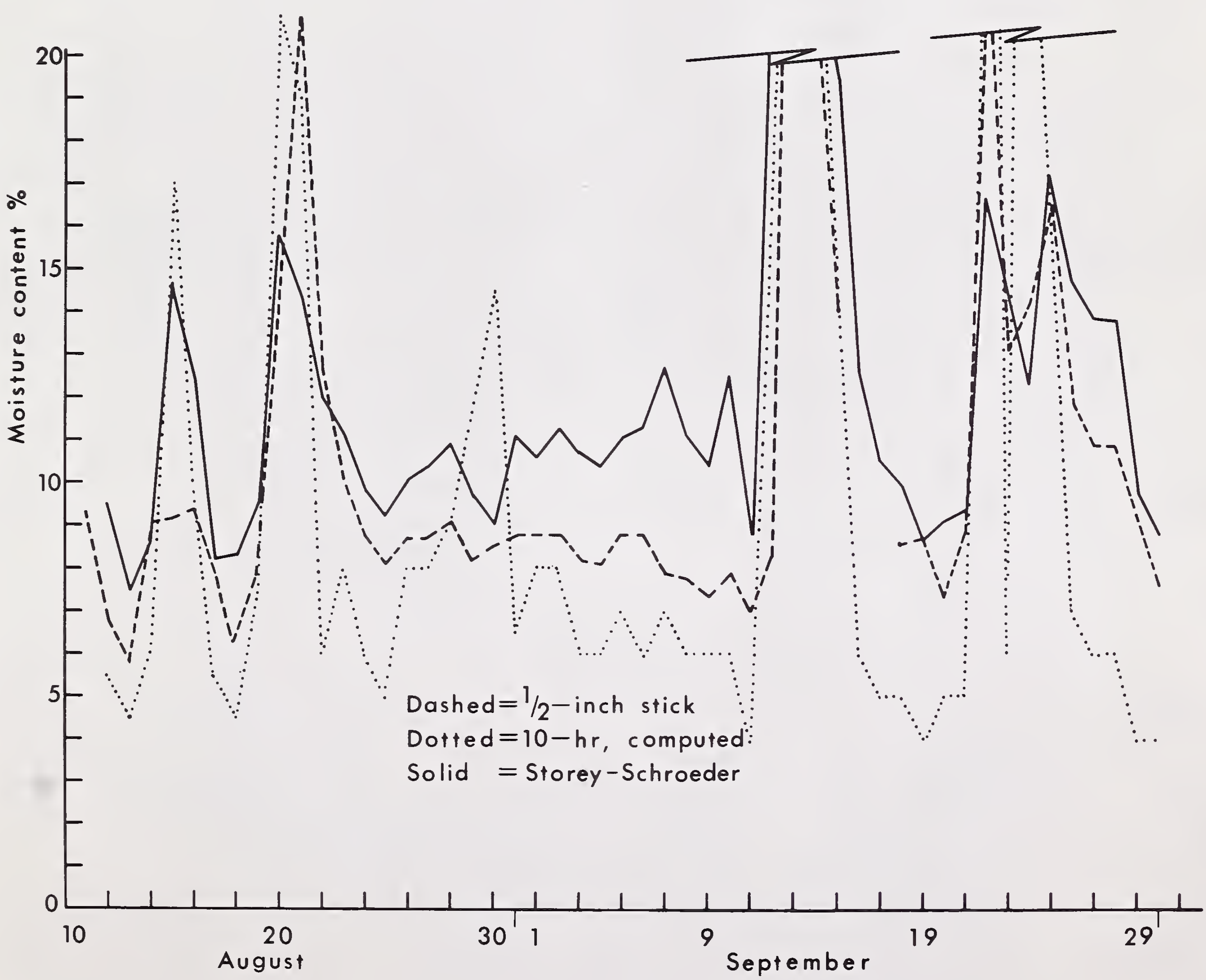
Figure 2.--Comparison between predicted 1-hour timelag fuel moistures.

tions of low relative humidity, they are more nearly like the wildland system and that under periods of high humidity, they are more like the equations developed by Storey. This is a desirable feature, since the wildland system was developed from data taken in arid regions and the equations developed by Storey are based on data collected in humid regions.

The 10-hour timelag fuel moisture calculations were compared directly with the half-inch stick observations and with Storey's prediction equation as modified by Schroeder (1969) (fig. 3). Comparison with the Storey-Schroeder equation shows reasonable agreement except after periods of precipitation. This is to be expected since the Storey-Schroeder equation does not consider precipitation duration. Comparison with the observed half-inch stick moisture contents is also reasonable provided one considers (1) the limitations introduced by the assumptions made in predicting the contribution of precipitation, and (2) the fact that the half-inch sticks have timelags varying from 12 to 15 hours.[8]

[8] Personal communication with William Fischer, Northern Forest Fire Laboratory, Missoula, Montana.

Figure 3.--Comparison between predicted and observed 10-hour timelag fuel moistures.



Summary

Prediction equations for the 1- and 10-hour timelag fuel moistures based on diffusion theory show good agreement with existing methods of computing these values. To insure computational stability, the prediction consists of solving the equations for short time periods and assembling these solutions into a final answer. The 1-hour timelag fuel moisture prediction equation uses 12 steps of 1/2 hour each; the 10-hour uses six steps of 4 hours each.

For the derivation of the tables used in the National Fire-Danger Rating System now being introduced, a diurnal cycle of temperature and humidity characteristic of continental climates was used. A principal advantage of this prediction approach is that tables can be derived specifically for areas which have a radically different diurnal weather cycle—areas which are subjected to marine air incursions, for example. This flexibility stands in sharp contrast to existing systems which exhibit strong bias toward the climatic regions in which they were developed.

The computed 1-hour timelag fuel moisture values compare well under conditions of low humidities with those derived from the California wildland system, and under high humidity conditions with those derived from the 1964 version of the National Fire-Danger Rating System.

The computed 10-hour timelag fuel moisture values compare well with field data taken from 1/2-inch ponderosa pine fuel moisture sticks.

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